

MeV Astronomy

The INTEGRAL Perspective



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INTEGRAL

INTERNATIONAL Gamma Ray Astrophysics Laboratory

- Launched in October 2002
- ESA Mission with U.S. participation 1995 - 2010
- Four scientific instruments with wide X-ray through soft γ -ray (3 keV – 10 MeV) + optical coverage
- Unprecedented combination of spectral and spatial resolution
- All instruments fully operational 12 years after launch.

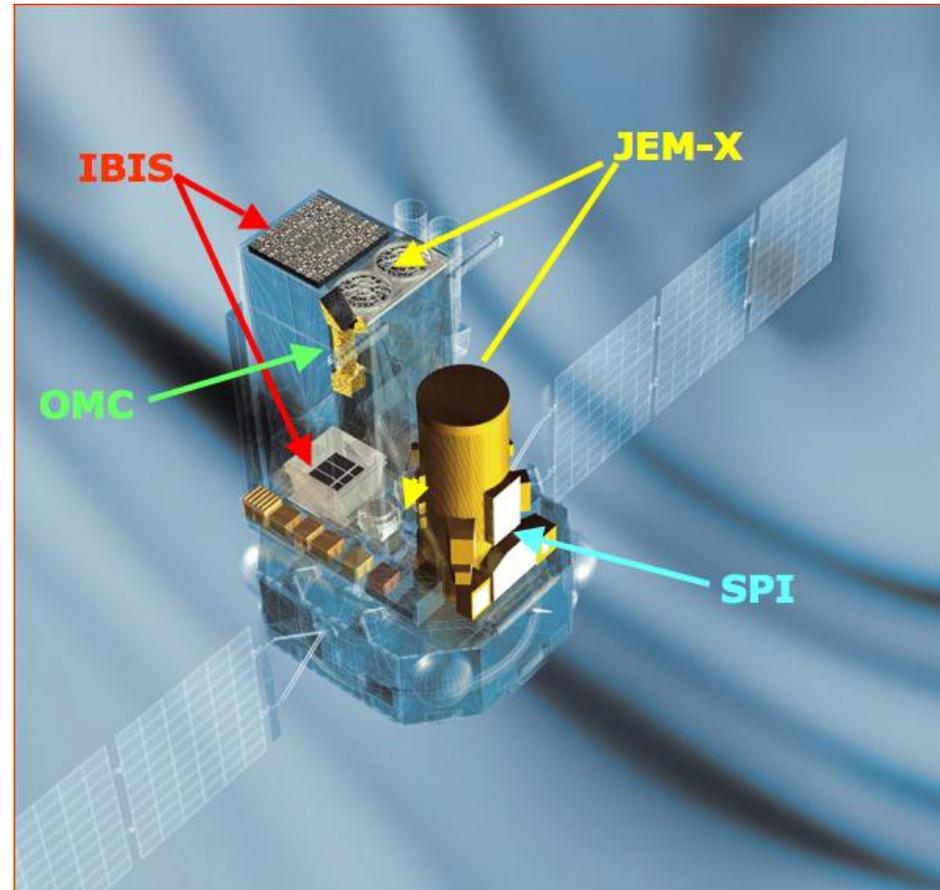


Scientific Instruments

Primary Instruments:

1. **SPI**: Spectrometer on INTEGRAL - High-Resolution Spectrometer (18 keV – 8 MeV)
2. **IBIS**: Imager on Board the INTEGRAL Satellite (15 keV – 10 MeV)

High Angular Resolution through Coded-Aperture Mask Technique



Secondary Instruments:

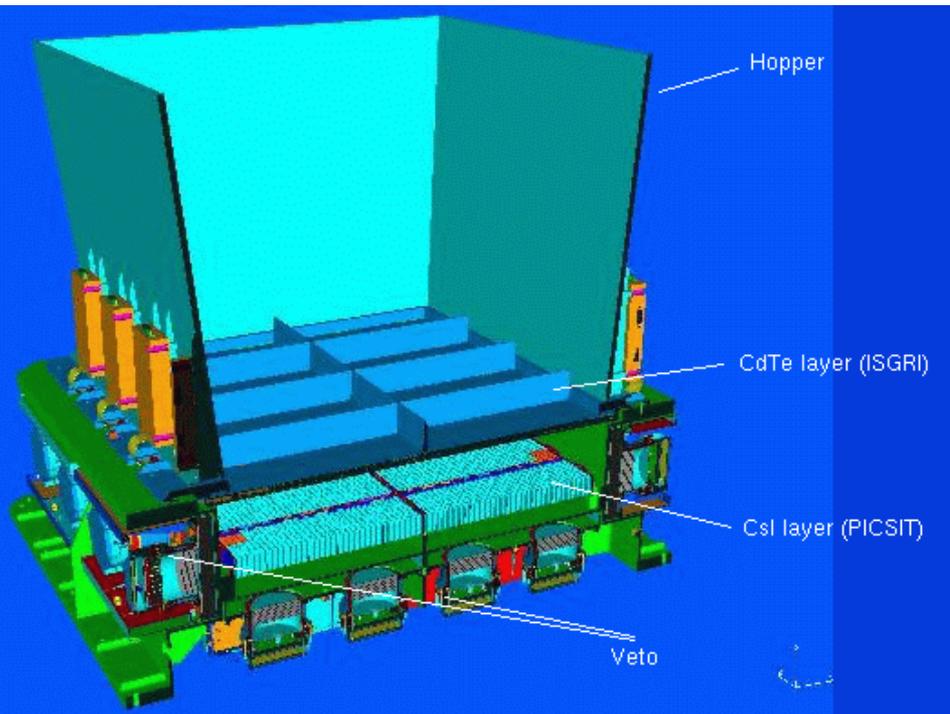
1. **JEM-X**: Joint European Monitor for X-rays (3 – 35 keV)
2. **OMC**: Optical Monitoring Camera



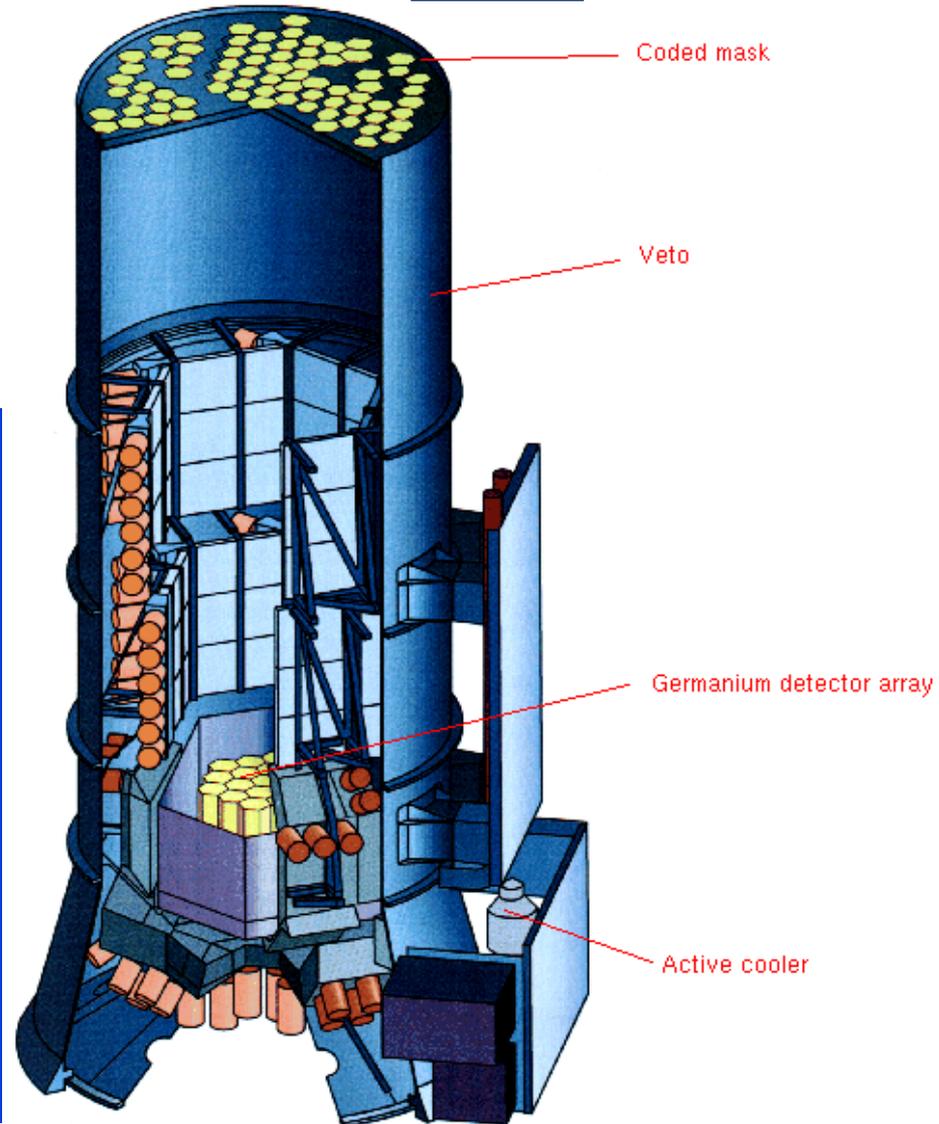
Scientific Instruments



IBIS



SPI



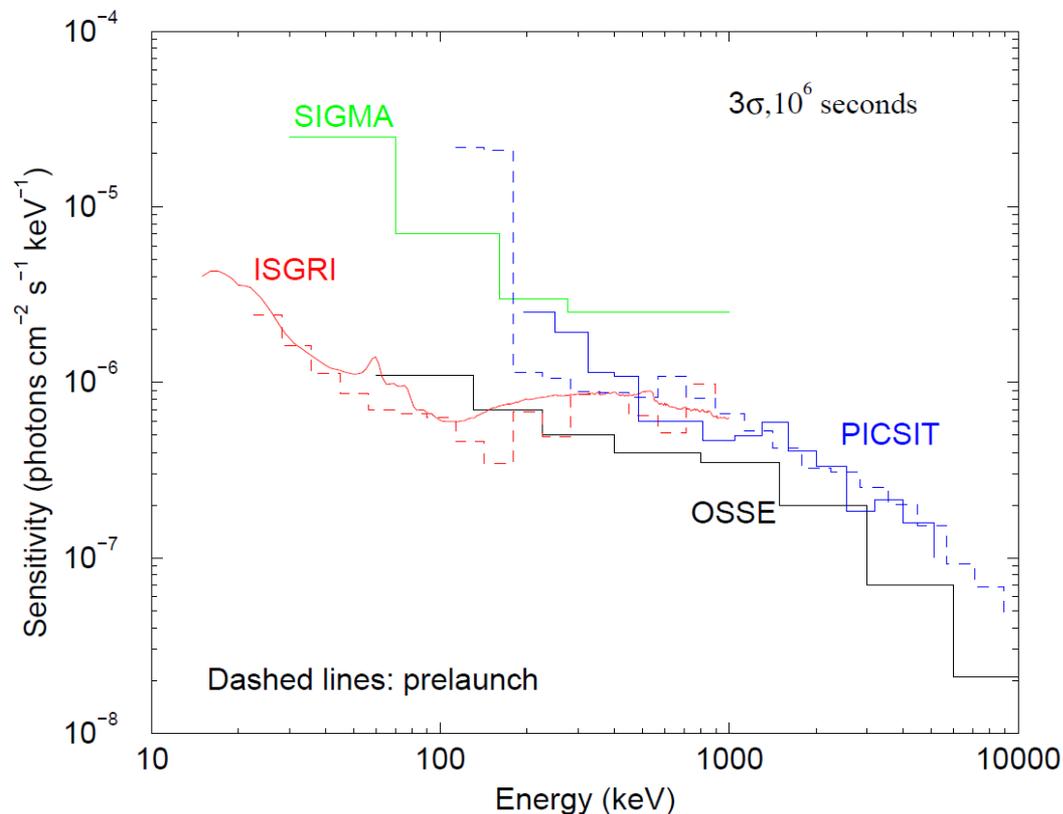
Scientific Instruments

Table 1: Summary of *INTEGRAL* Instrument Characteristics^a

	SPI	IBIS	JEM-X	OMC
Field of View (fully coded)	16°	8.3° × 8°	4.8°	5° × 5°
Angular Resolution (FWHM)	2.5°	12'	3'	23''
Energy Range	18 keV - 8 MeV	15 keV - 10 MeV	3 - 35 keV	500 - 600 nm (V filter)
Energy Resolution (FWHM)	1.93 keV @500 keV	8.0 keV @100keV	2.0 keV @22 keV	—

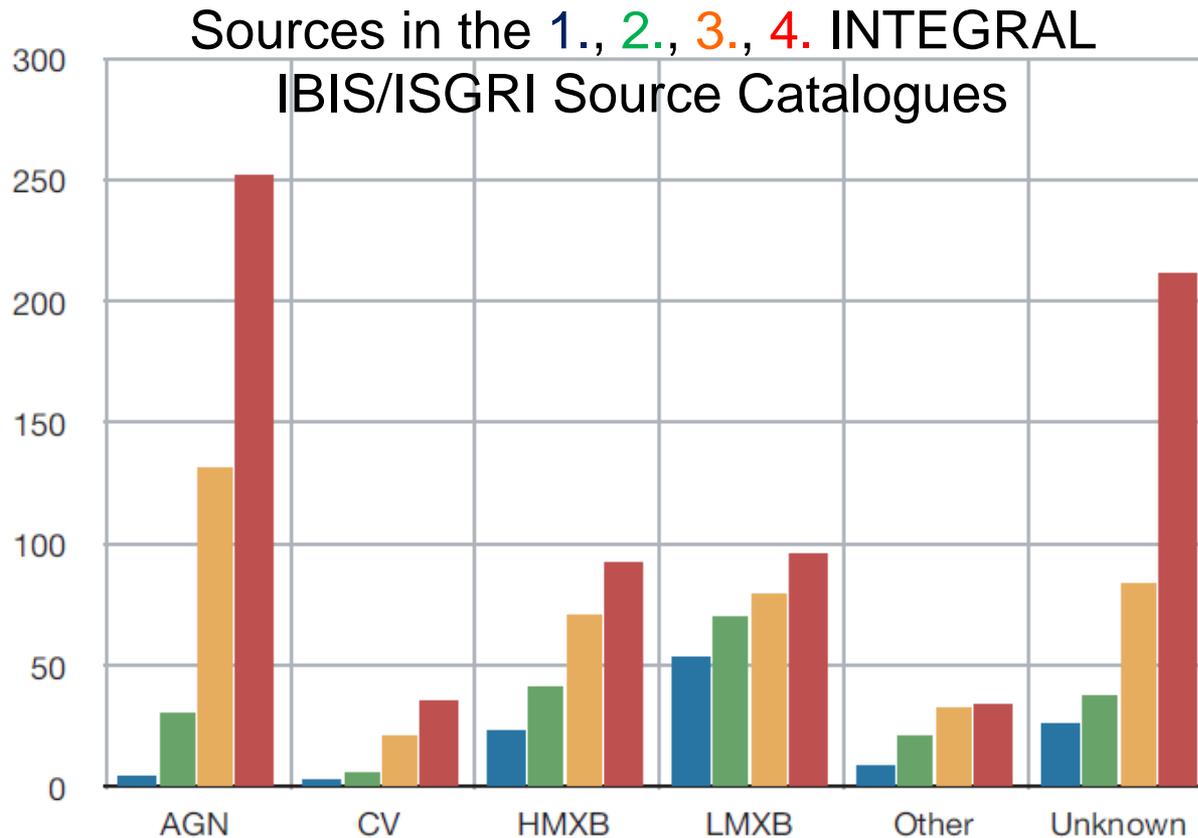
^aFull description at http://www.sciops.esa.int/index.php?project=INTEGRAL&page=About_INTEGRAL_Instruments

Continuum sensitivities

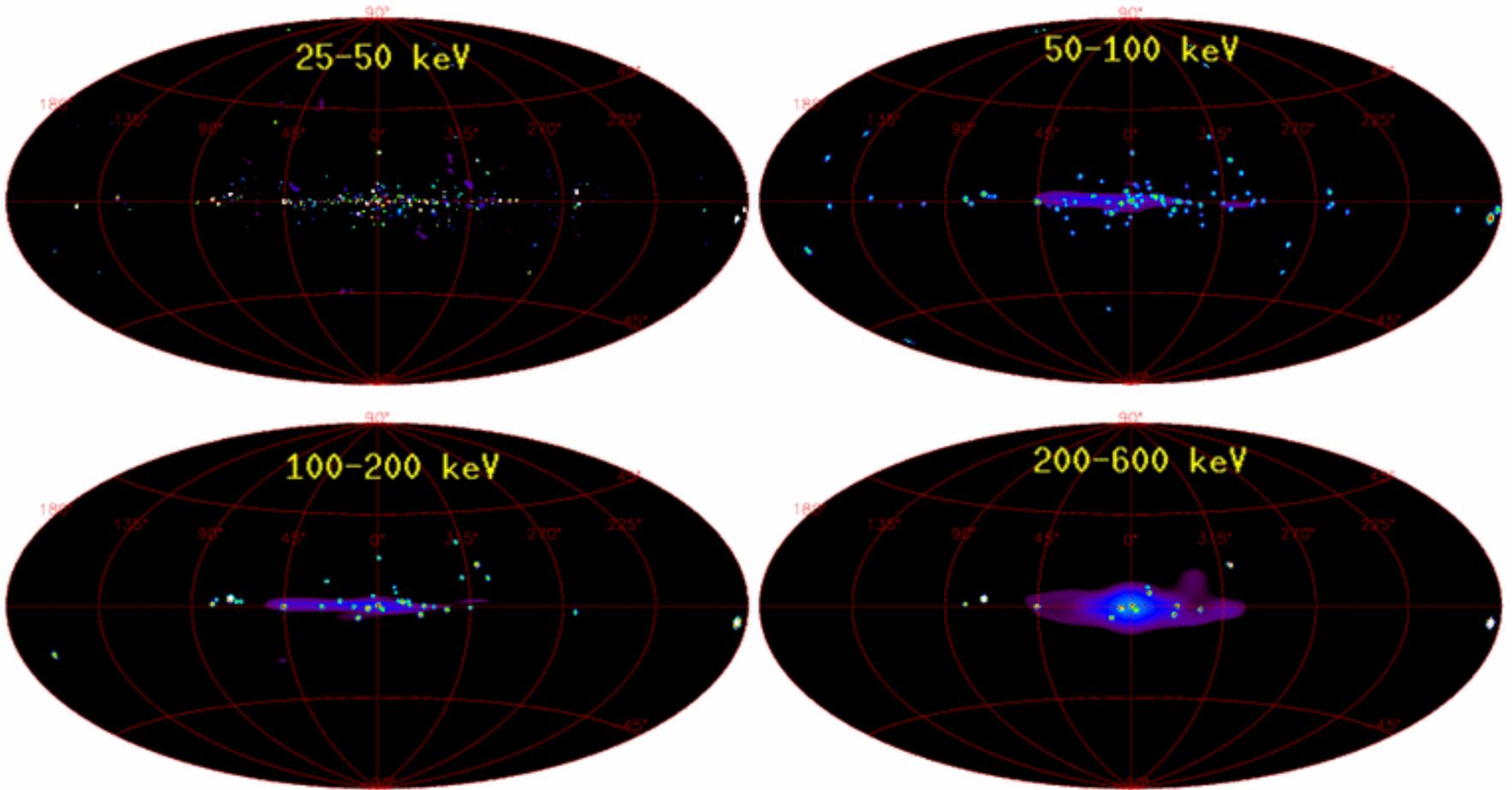


Primary Scientific Goals

- High spatial and spectral resolution observations of Galactic γ -ray lines
- Hard X-ray observations of obscured (Galactic and extragalactic) X-ray sources
- Potential for X-ray polarimetry



The INTEGRAL Sky



INTEGRAL Picture
of the Month
March 2008



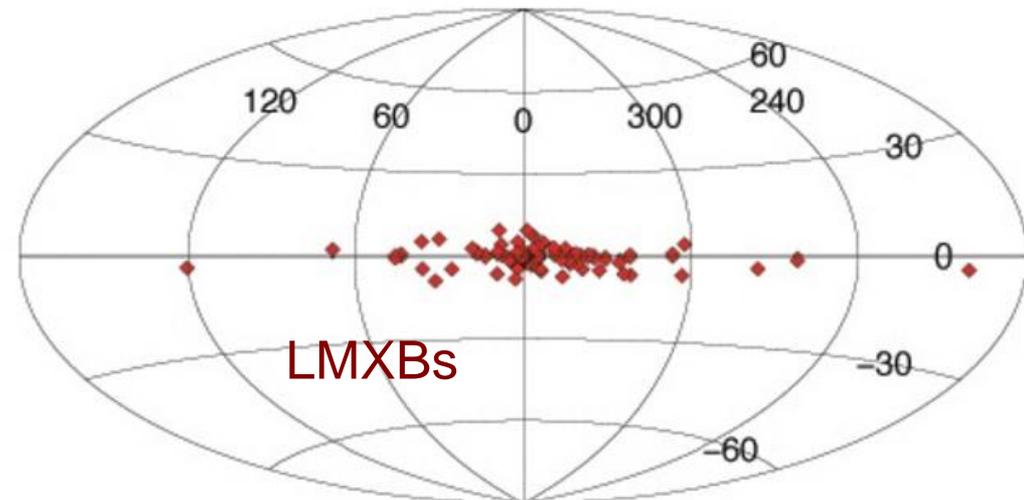
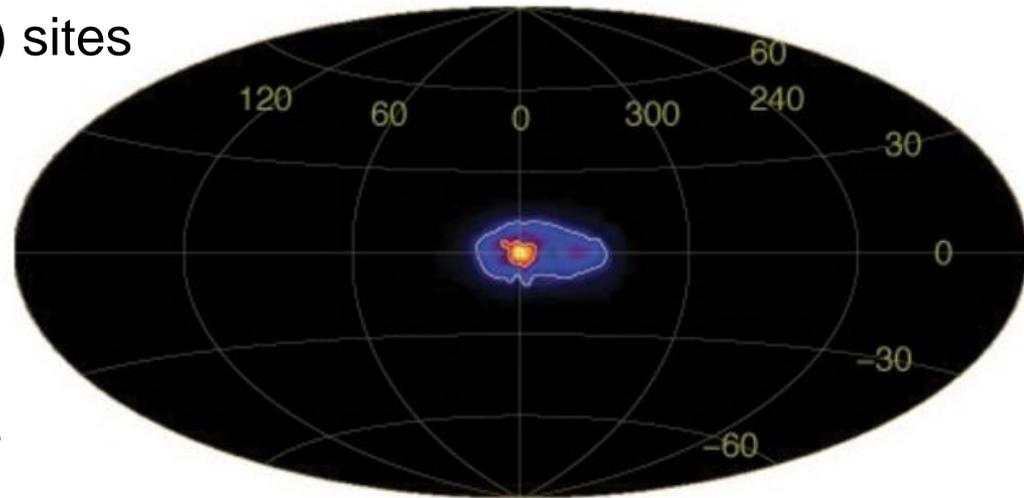
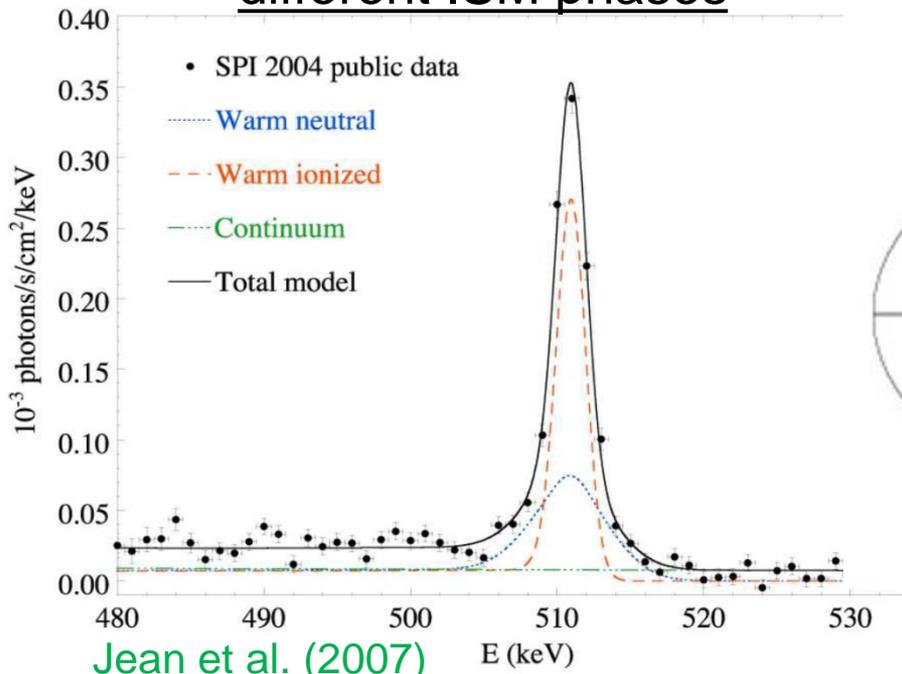
Gamma-Ray Lines – 511 keV

e^+e^- annihilation \rightarrow

Sources of e^+ + annihilation (target) sites

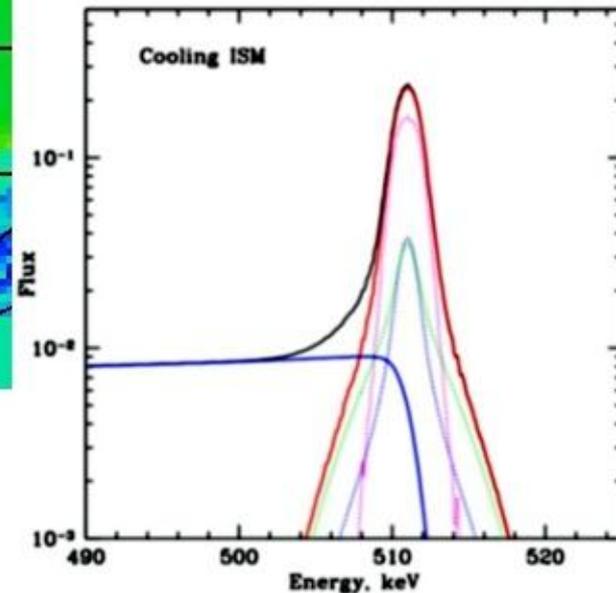
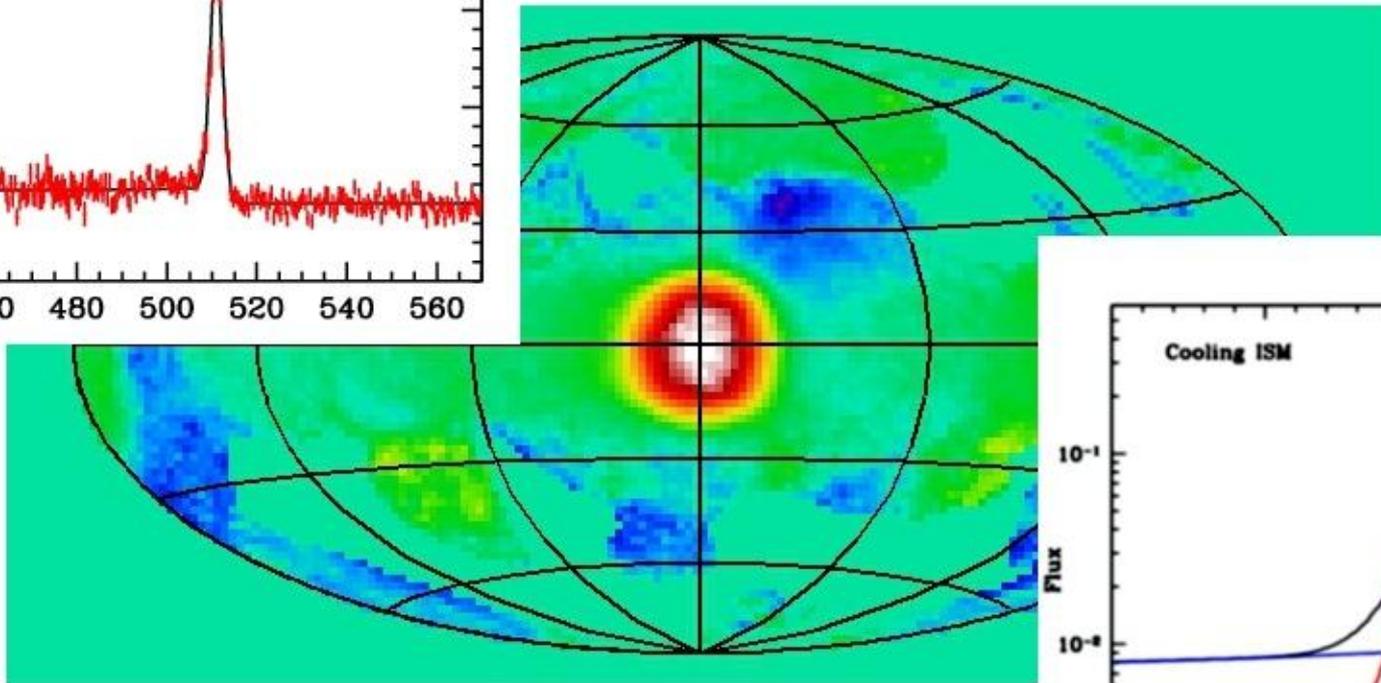
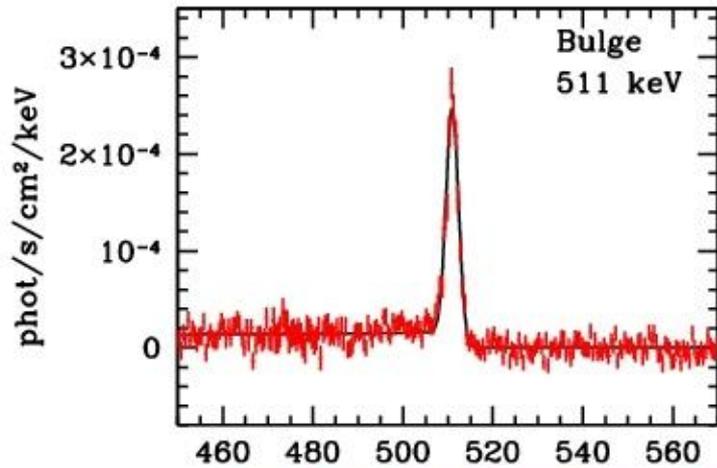
Sources of e^+ generally thought to be SNRs – but different distribution than ^{26}Al line...

Annihilation in a combination of different ISM phases



INTEGRAL Picture of the Month February 2008

Gamma-Ray Lines – 511 keV



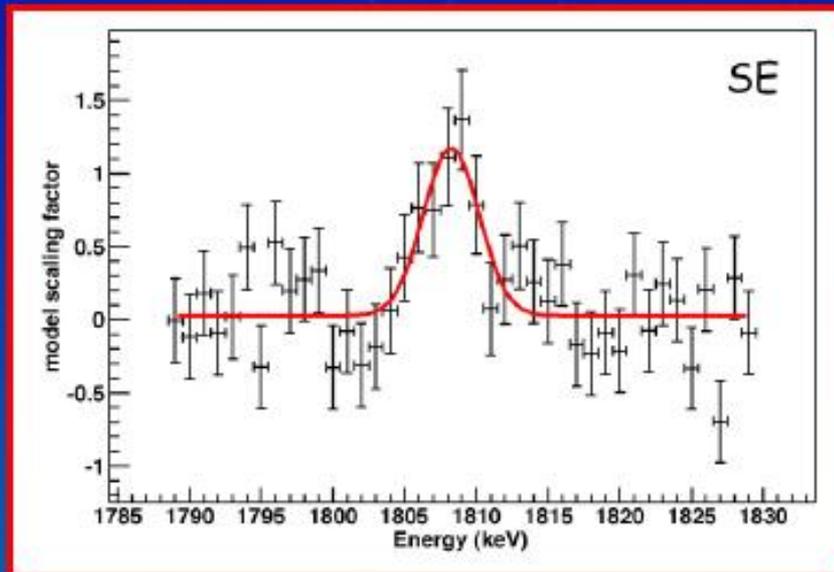
INTEGRAL Picture of the Month May 2011

Gamma-Ray Lines – ^{26}Al

Unveiling massive star nucleosynthesis in Cygnus X

1809 keV gamma-ray line emission from radioactive ^{26}Al decay

SPI/INTEGRAL 1809 keV line spectrum of Cygnus X



Flux : $(7.2 \pm 1.8) \times 10^{-5} \text{ ph cm}^{-2} \text{ s}^{-1}$
Position : $1808.4 \pm 0.3 \text{ keV} \Rightarrow v_{\text{rad}} = -41 \pm 50 \text{ km s}^{-1}$
Width : $3.3 \pm 1.3 \text{ keV} \Rightarrow \Delta v = 550 \pm 210 \text{ km s}^{-1}$

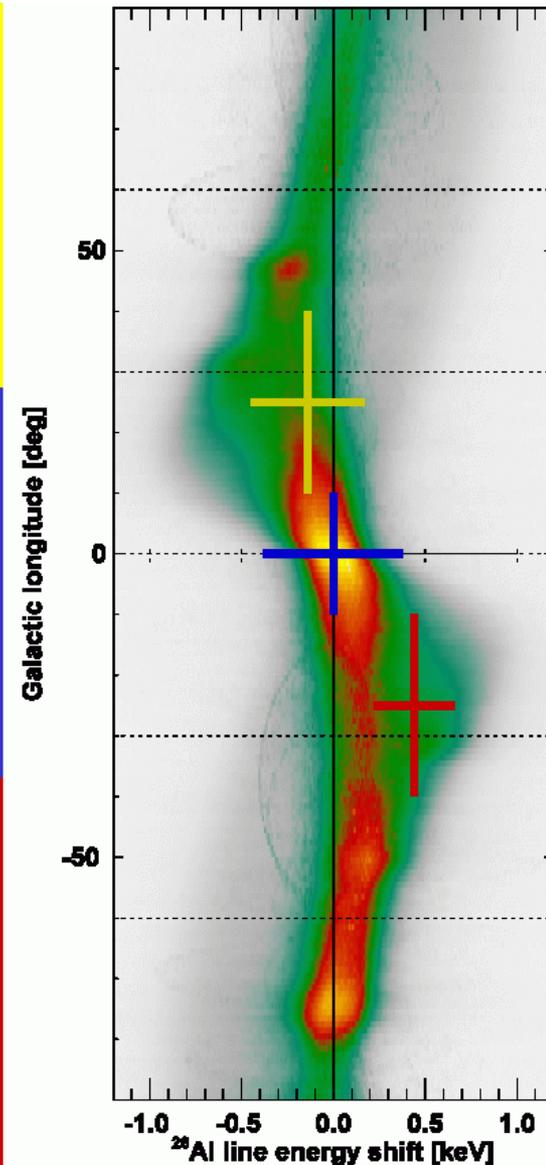
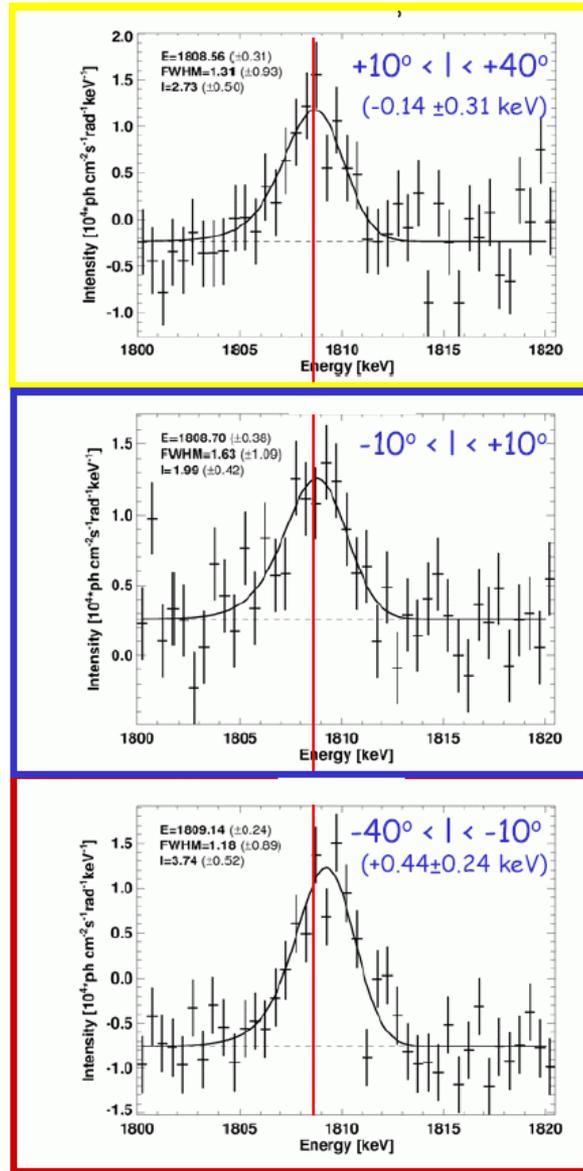


DRAO radio image of ionising massive star clusters in Cygnus X that are at the origin of the ^{26}Al production detected by SPI

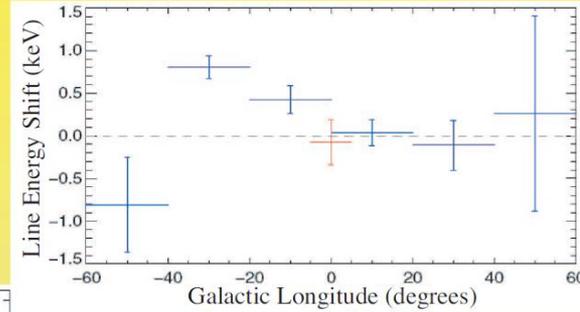
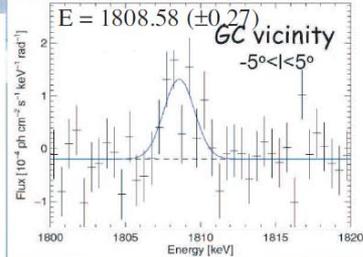
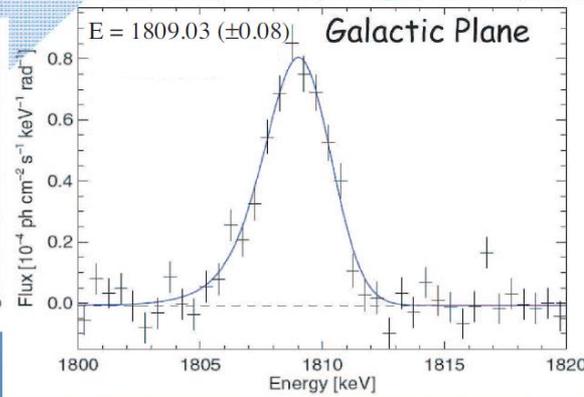
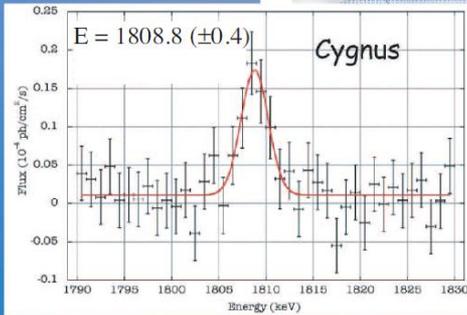
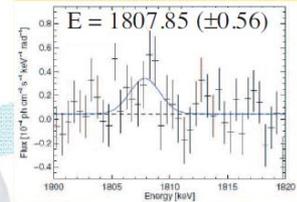
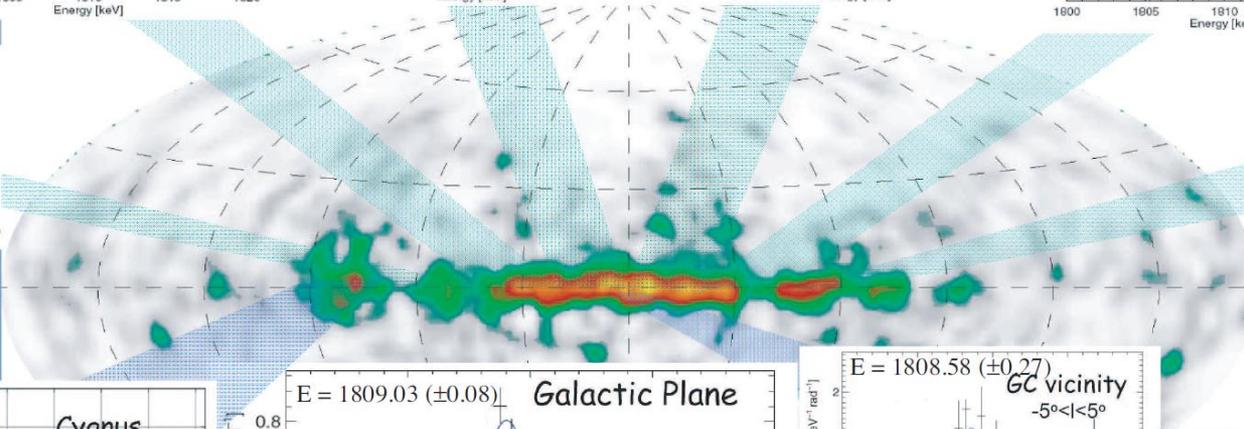
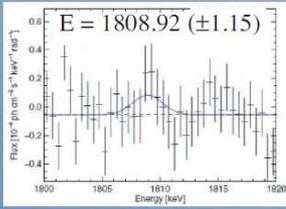
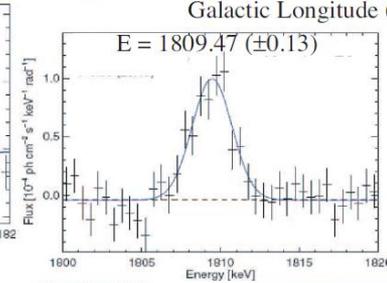
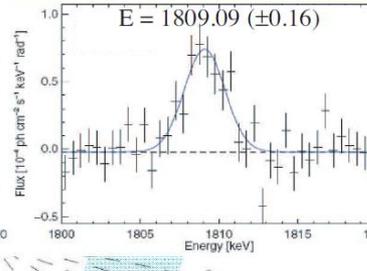
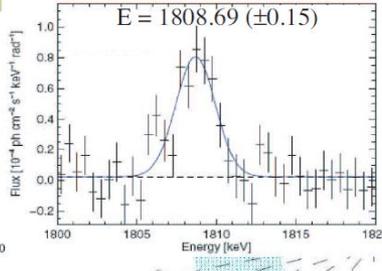
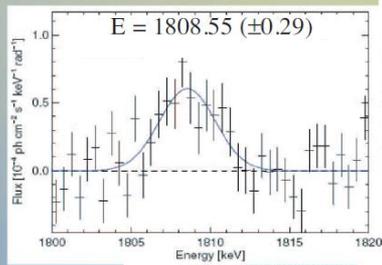
Gamma-Ray Lines – ^{26}Al

SPI

- First detailed spectroscopy of the ^{26}Al line
- Resolving Galactic rotation
- Identified core-collapse supernovae and their pre-explosion states as primary sources of ^{26}Al .



^{26}Al Spectra along the Plane of the Galaxy

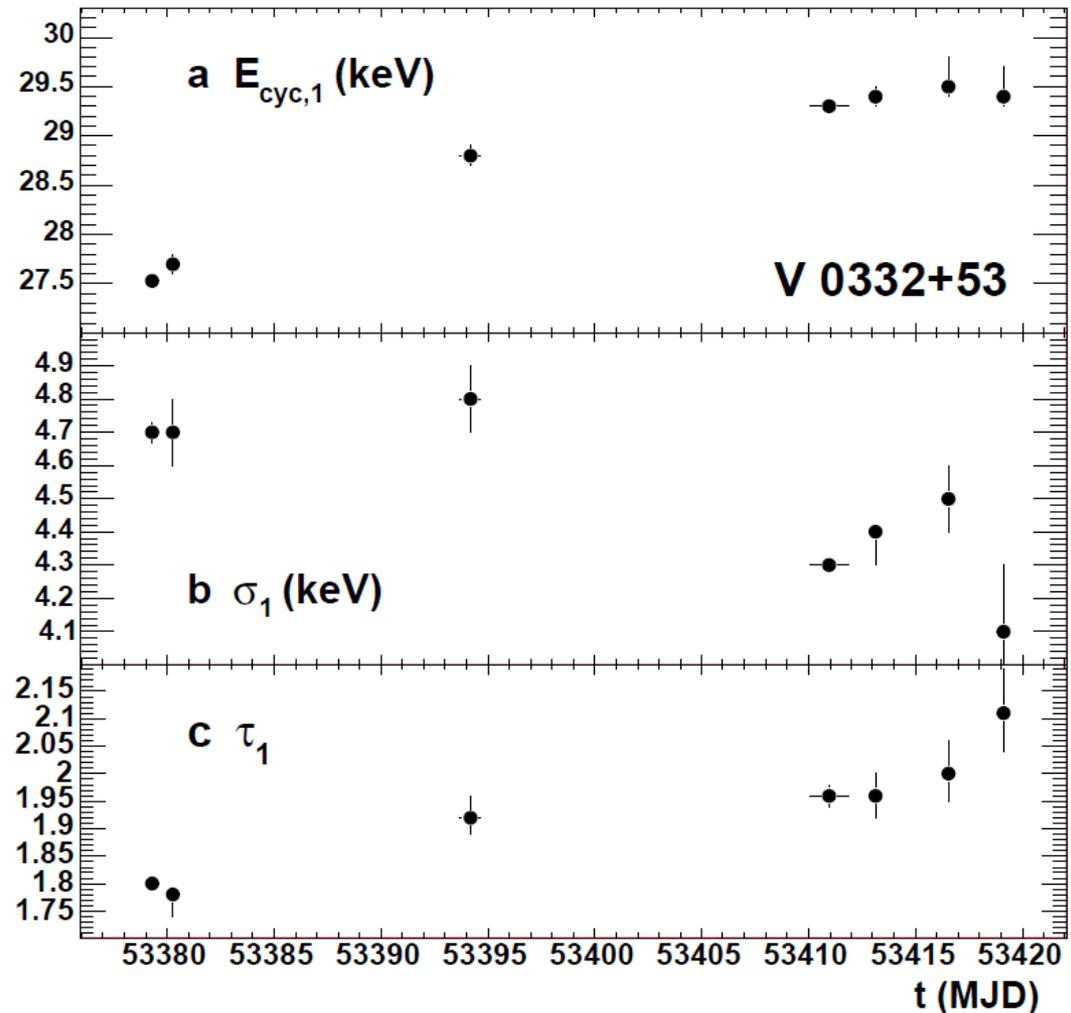
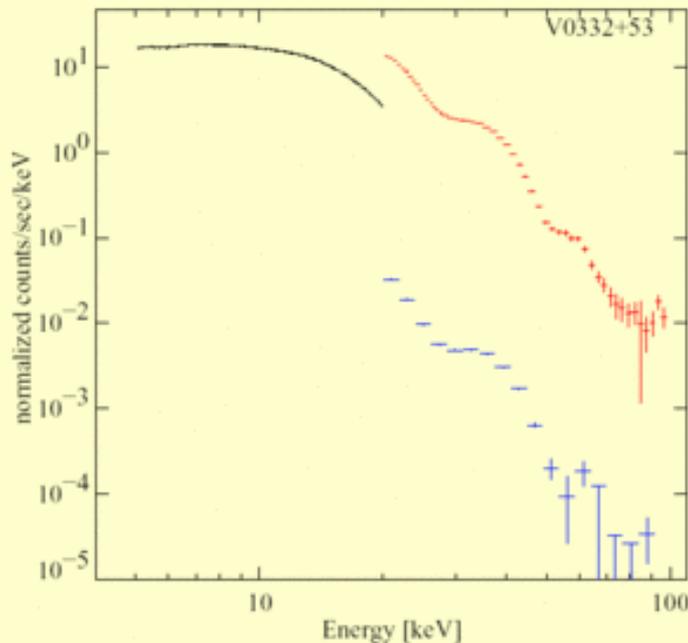


©SPI Team 2009

- Wang et al., A&A Vol. 496 (2009)
- Martin et al., A&A Vol. tbd (2009)

Cyclotron Lines

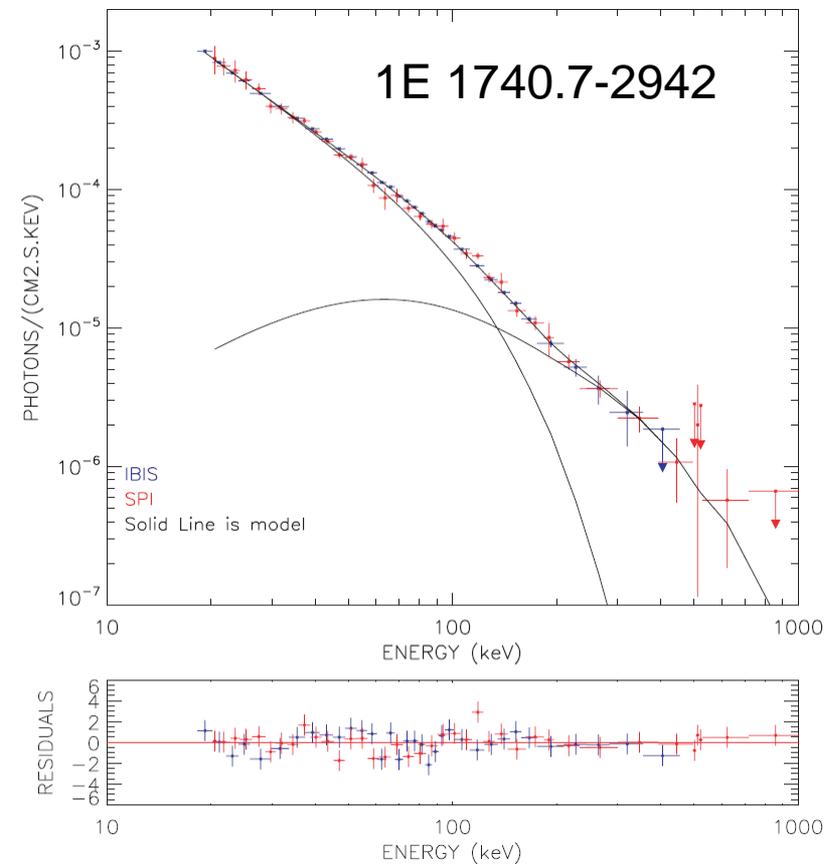
- At $\sim 10 - 100$ keV for $B \sim 10^{12}$ G
- Direct diagnostic of B and physics of accretion column
- Variability constrains the location of line production region



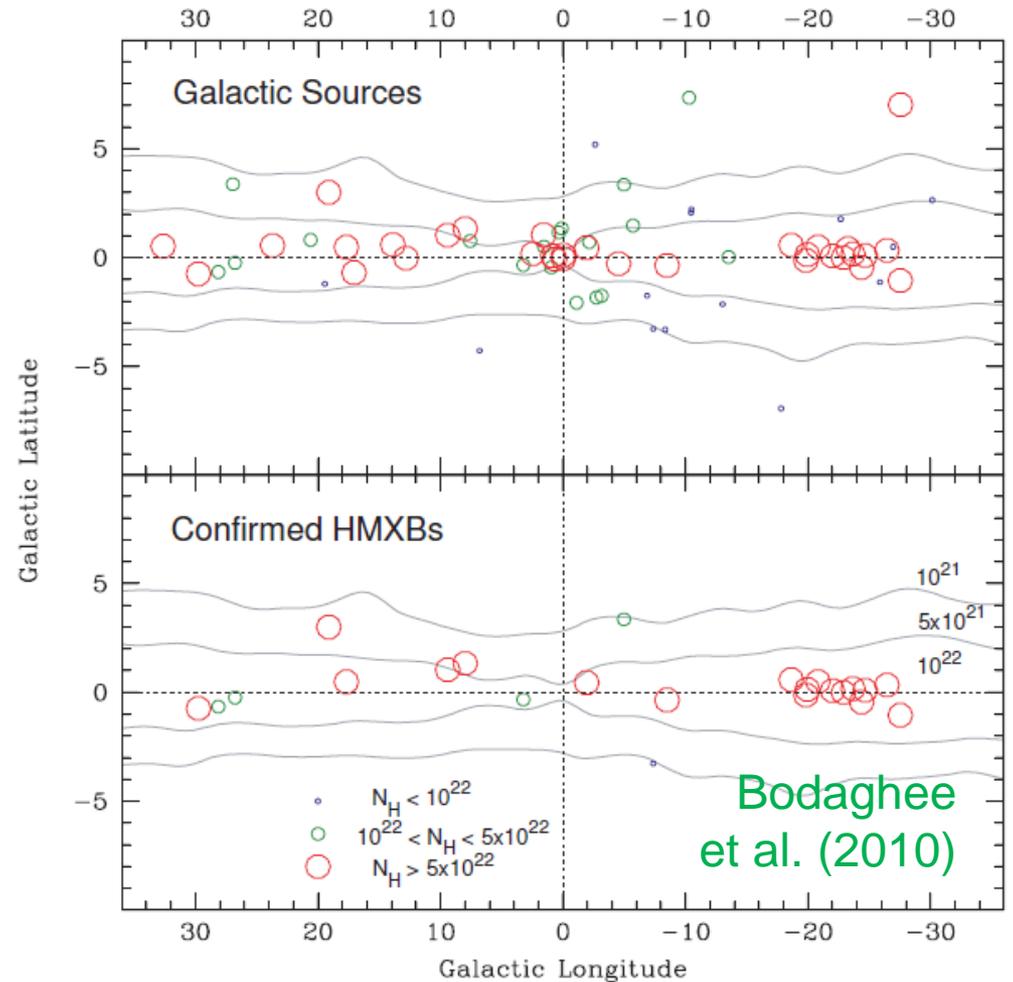
Mowlavi et al. (2006)

Heavily Obscured Galactic Sources

Hard X-ray coverage allows for observations of near-GC sources and other XRBs up to > 100 keV.



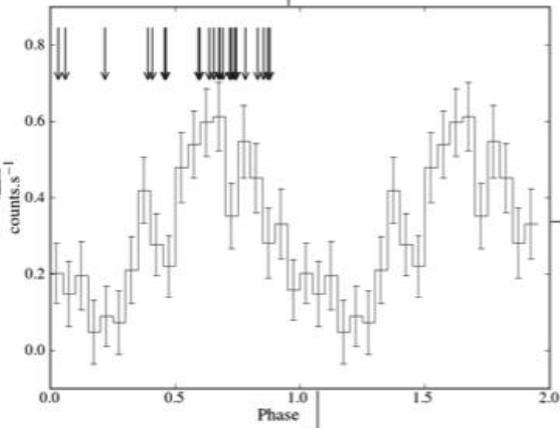
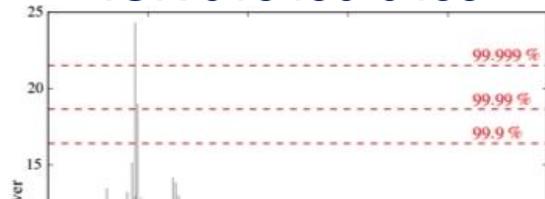
Bouchet et al. (2009)



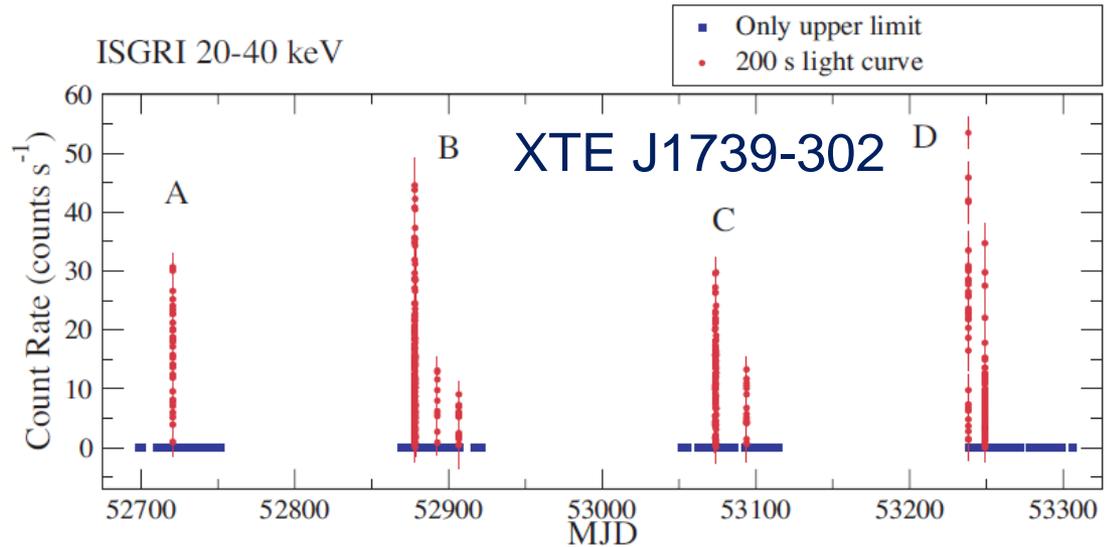
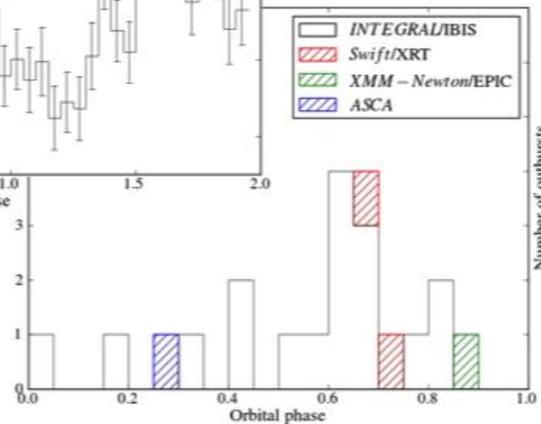
X-ray N_H often larger than inferred from optical extinction
→ Local absorption from companion wind

Supergiant Fast X-Ray Transients

IGR J18450-0435



INTEGRAL Picture of the Month August 2013

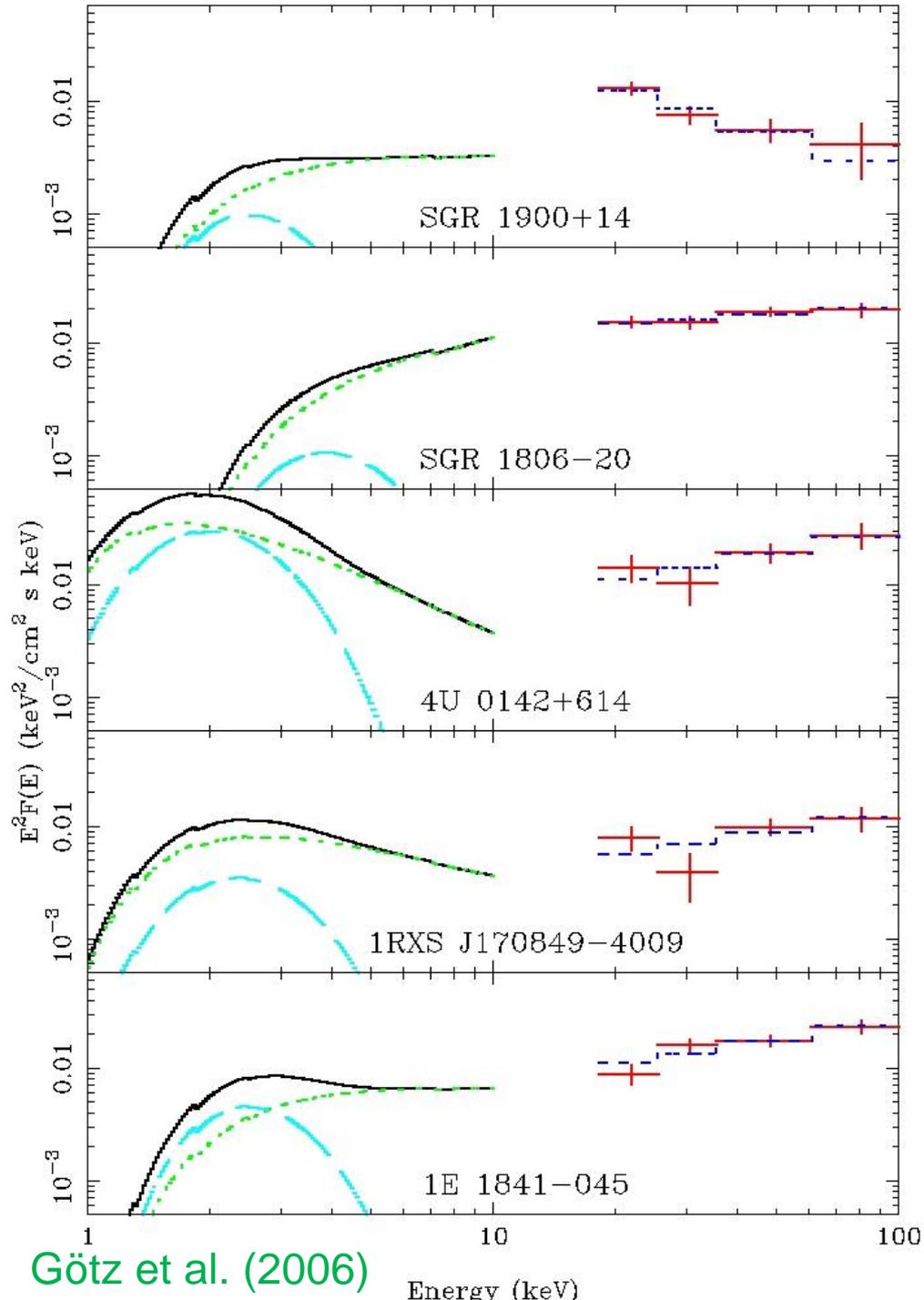


Blay et al. (2008)

Discovered by
INTEGRAL:
 Highly variable HMXBs;
 possibly triggered by
 clumpy winds.

Magnetars SGRs, AXPs

- $B > 10^{14}$ G
- Persistent emission + rapid outbursts
- INTEGRAL detects the faintest SGR bursts (about 1000 detected so far)
- First alert on the giant flare of SGR 1806-20 came from INTEGRAL
- Quiescent emission up to 200 keV

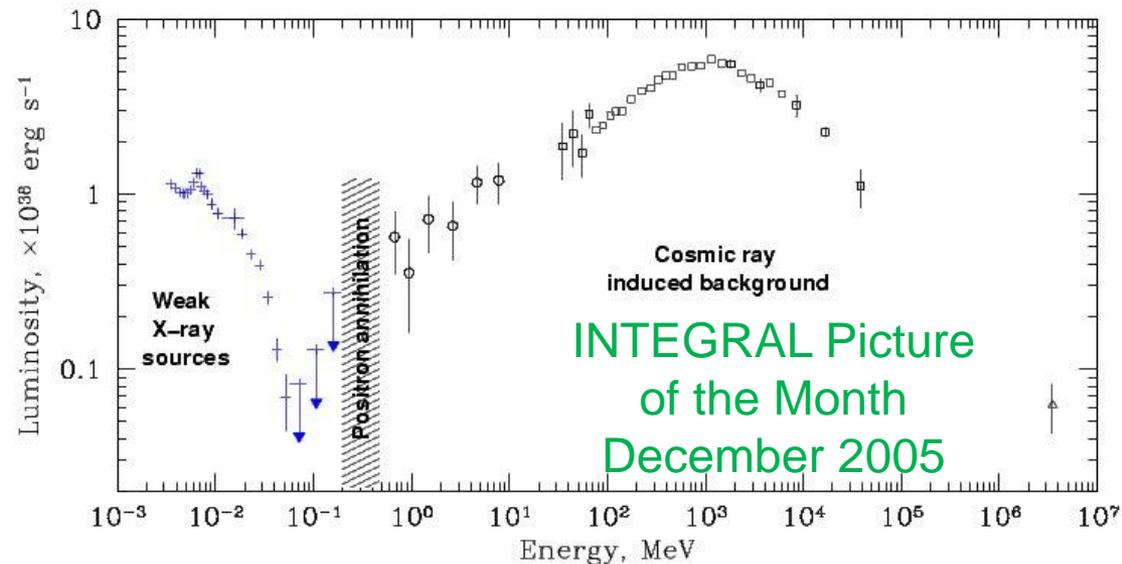
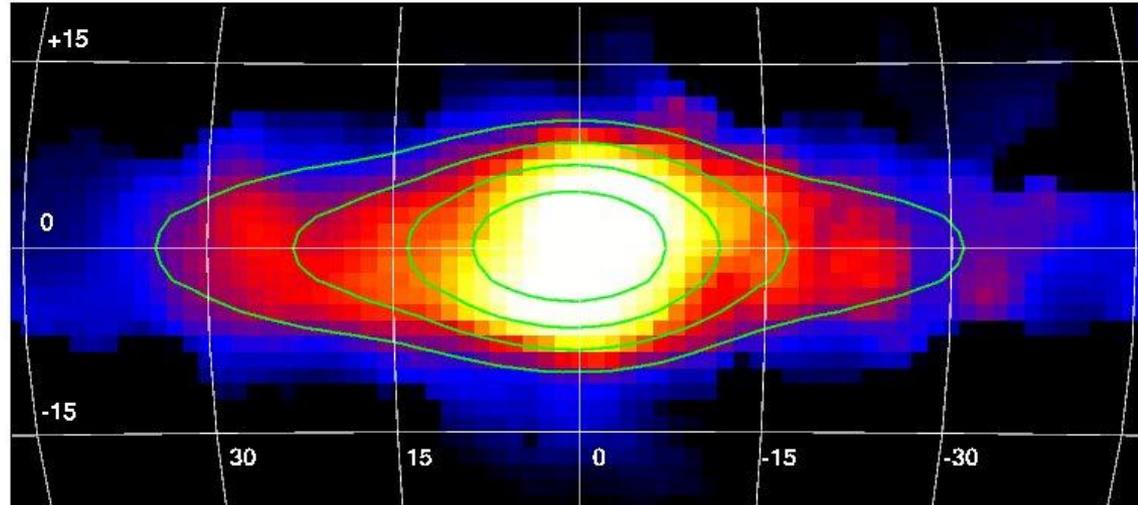


Götz et al. (2006)

Energy (keV)

Cataclysmic Variables (CVs)

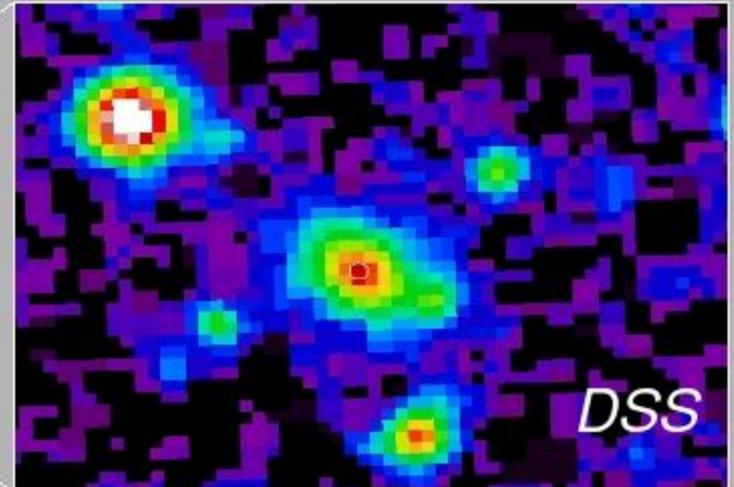
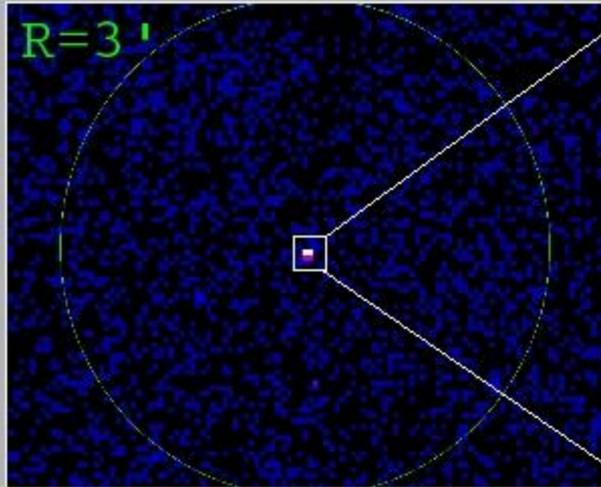
- Roche-lobe filling star transferring matter to a White Dwarf (WD)
- Over 20 detected by INTEGRAL
- Most are Intermediate Polars (IPs), i.e., intermediate-B ($\sim 10^6$ G) WDs.
- Thermal bremsstrahlung from WD surface + emission from shock-heated material in the accretion column
- CVs might make significant contribution to Galactic Ridge X-ray Emission (GRXE)
- Symbiotic Binaries identified with accretion onto high-mass ($\sim 1.35 M_{\odot}$) non-magnetic WDs - Candidate recurrent novae – Type Ia progenitors?



Heavily Obscured AGNs

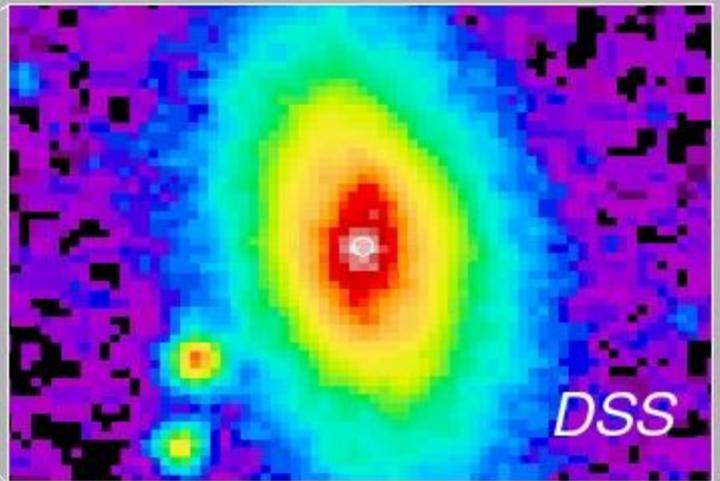
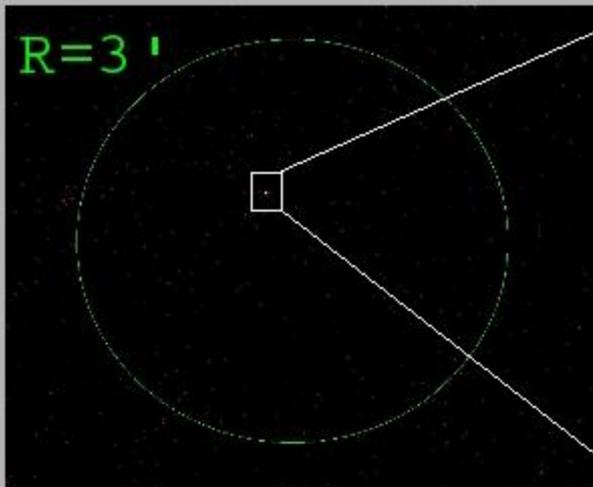
IGR J19473-4452 / 2MASS Galaxy / $z=0.05$

Log NH ~ 23



IGR J13091+1137 / NGC 4992 / $z=0.0225$

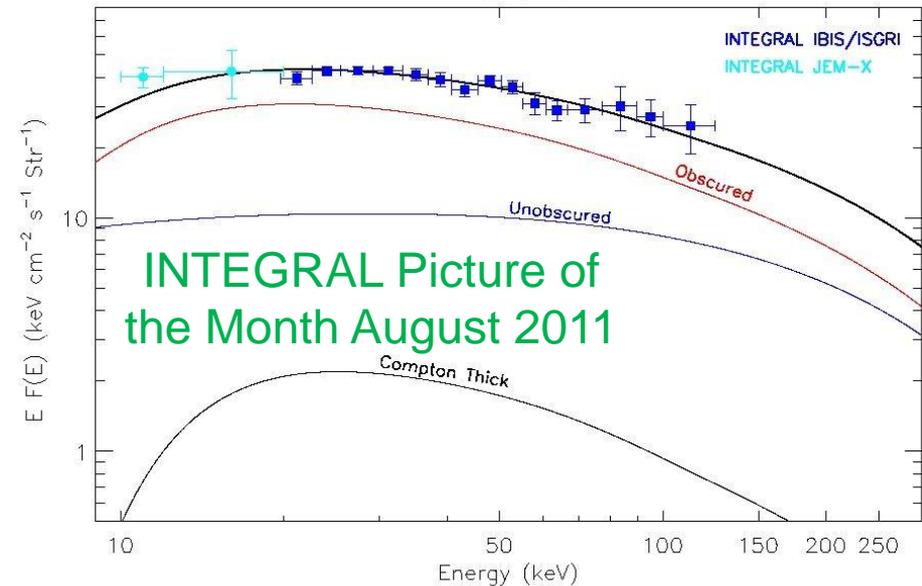
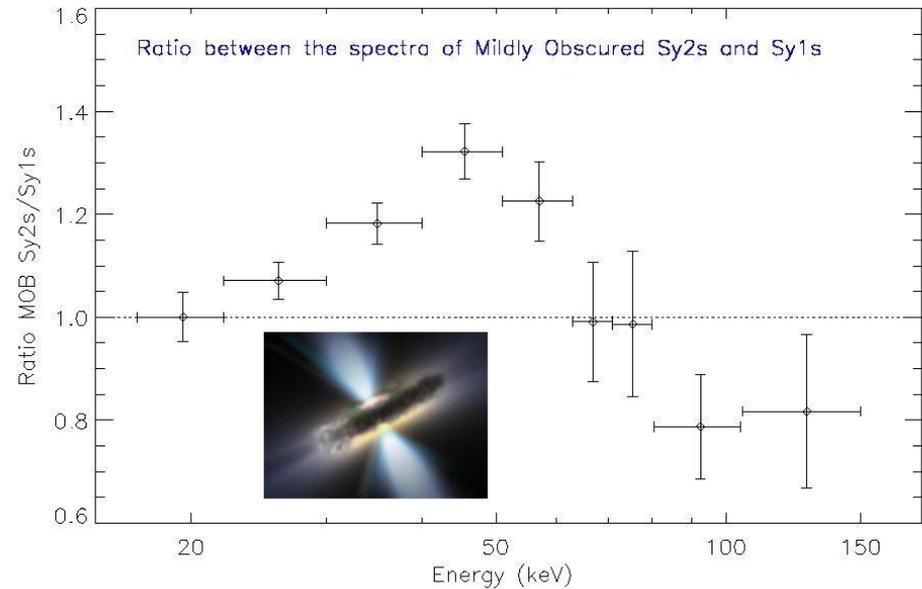
Log NH ~ 24



INTEGRAL Picture
of the Month
November 2005

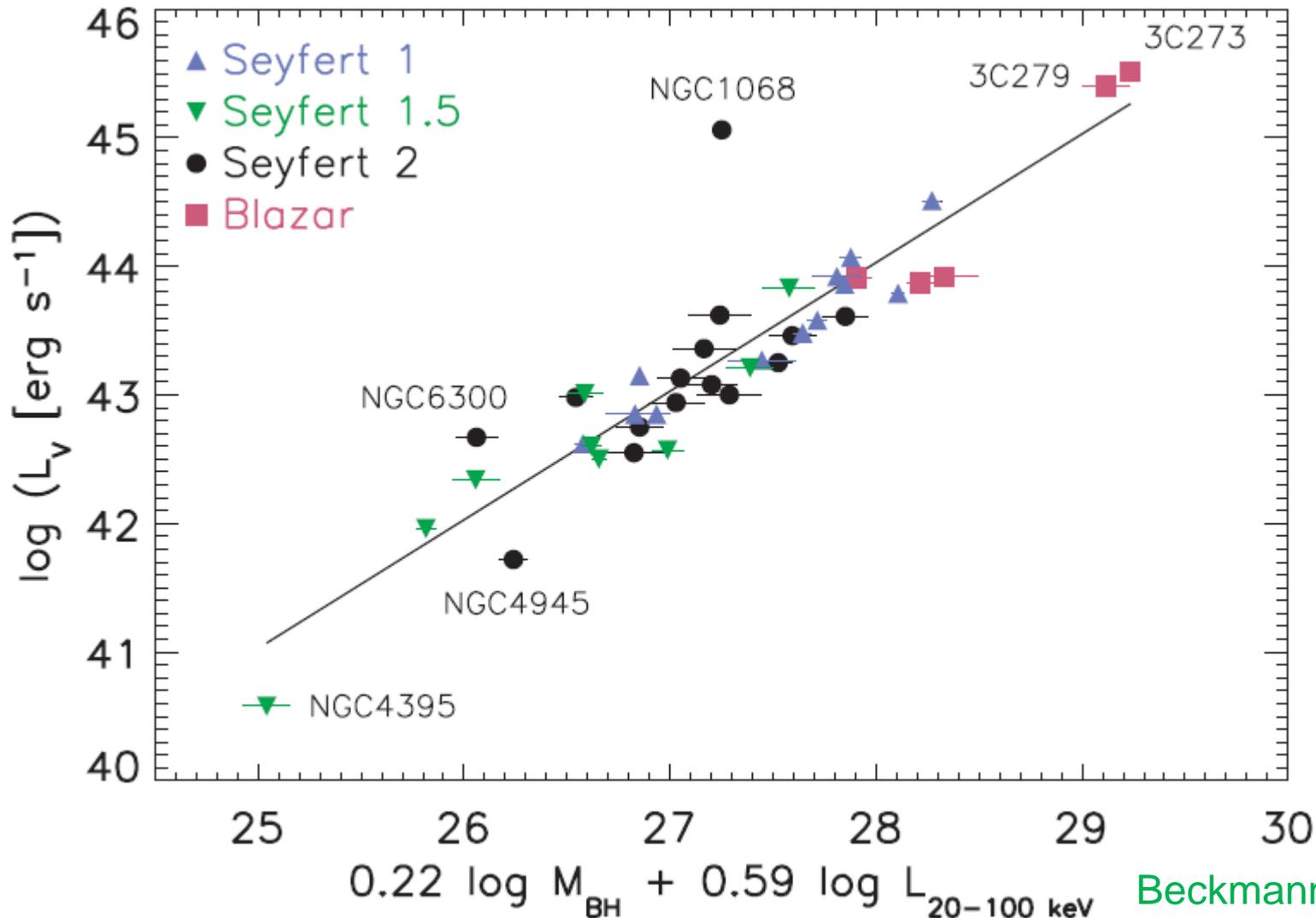
Heavily Obscured AGN

- High-quality hard X-ray spectra from over 100 AGN, especially heavily absorbed (type-2) AGN
- Results consistent with thermal Comptonization in moderate Compton depth ($\tau \sim 0.5$), mildly relativistic corona
- Fraction of Compton thick sources smaller than expected from population synthesis models
→ hard Cosmic X-Ray background can not be entirely due to unresolved obscured AGN



AGN Studies

The optical – X-ray – M_{BH} Fundamental Plane

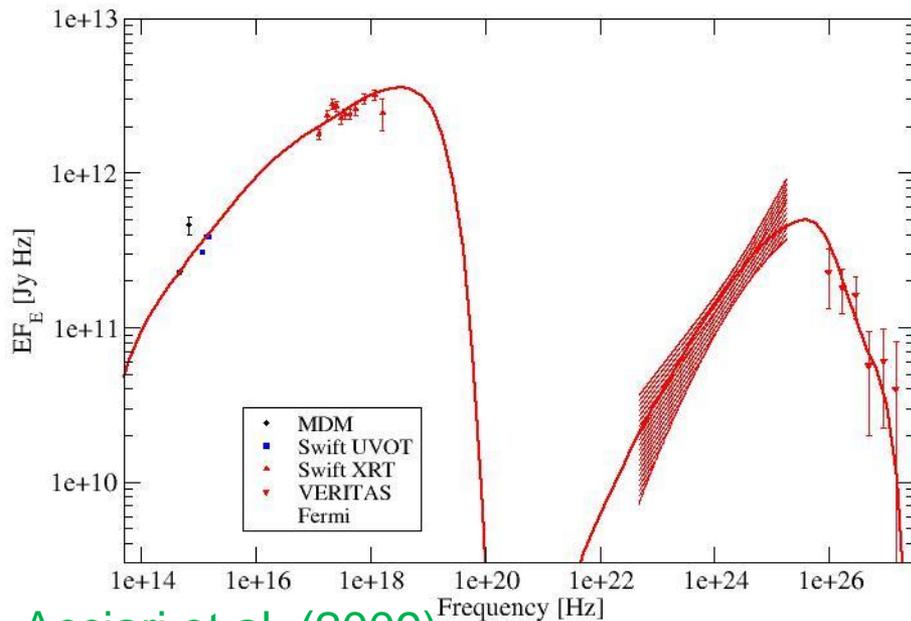


Beckmann et al. (2009)

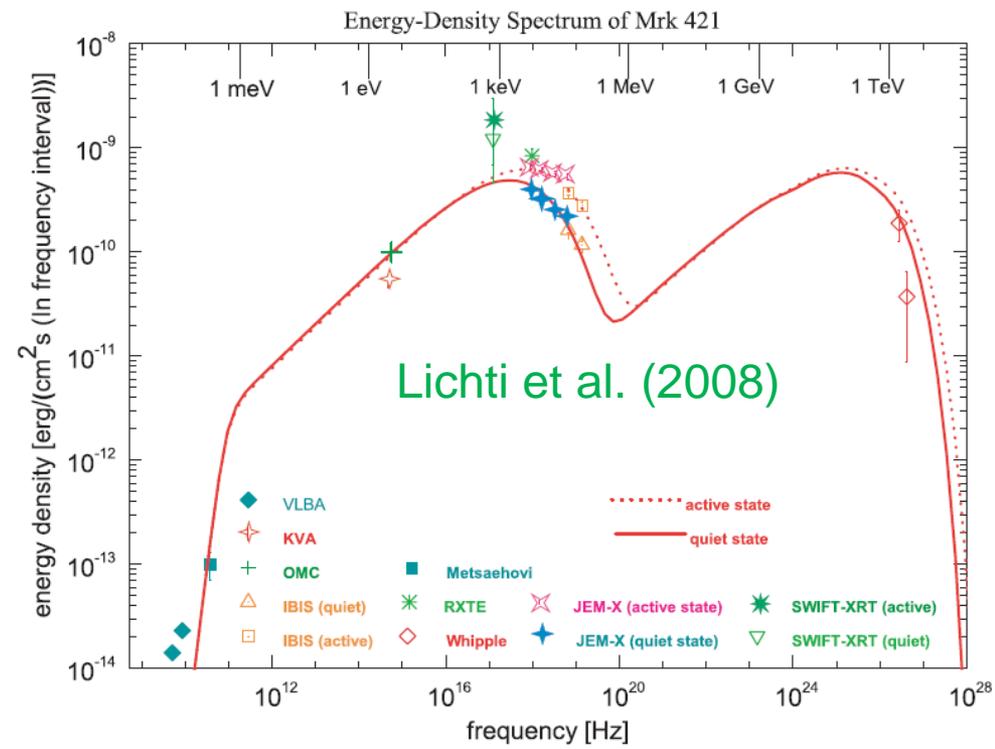
Blazars

- Large Energy range and MeV coverage important to resolve synchrotron peak in HBLs.

RGB J0710+591

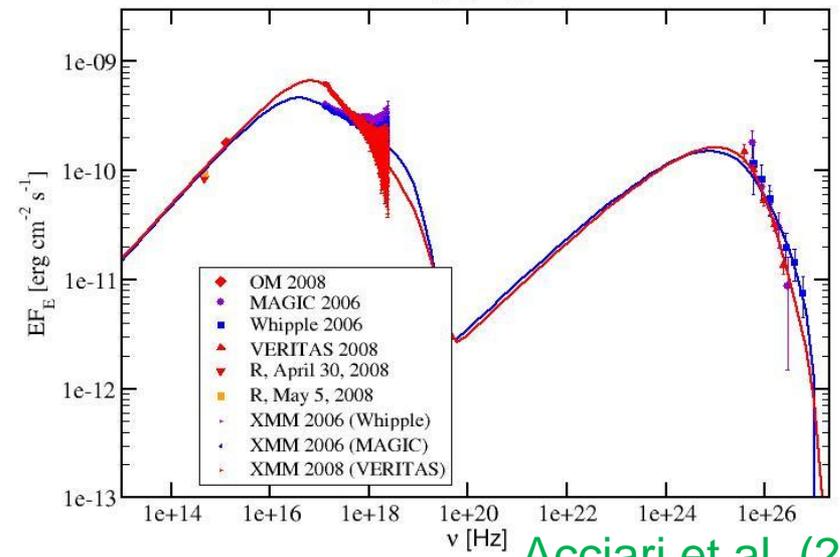


Acciari et al. (2009)



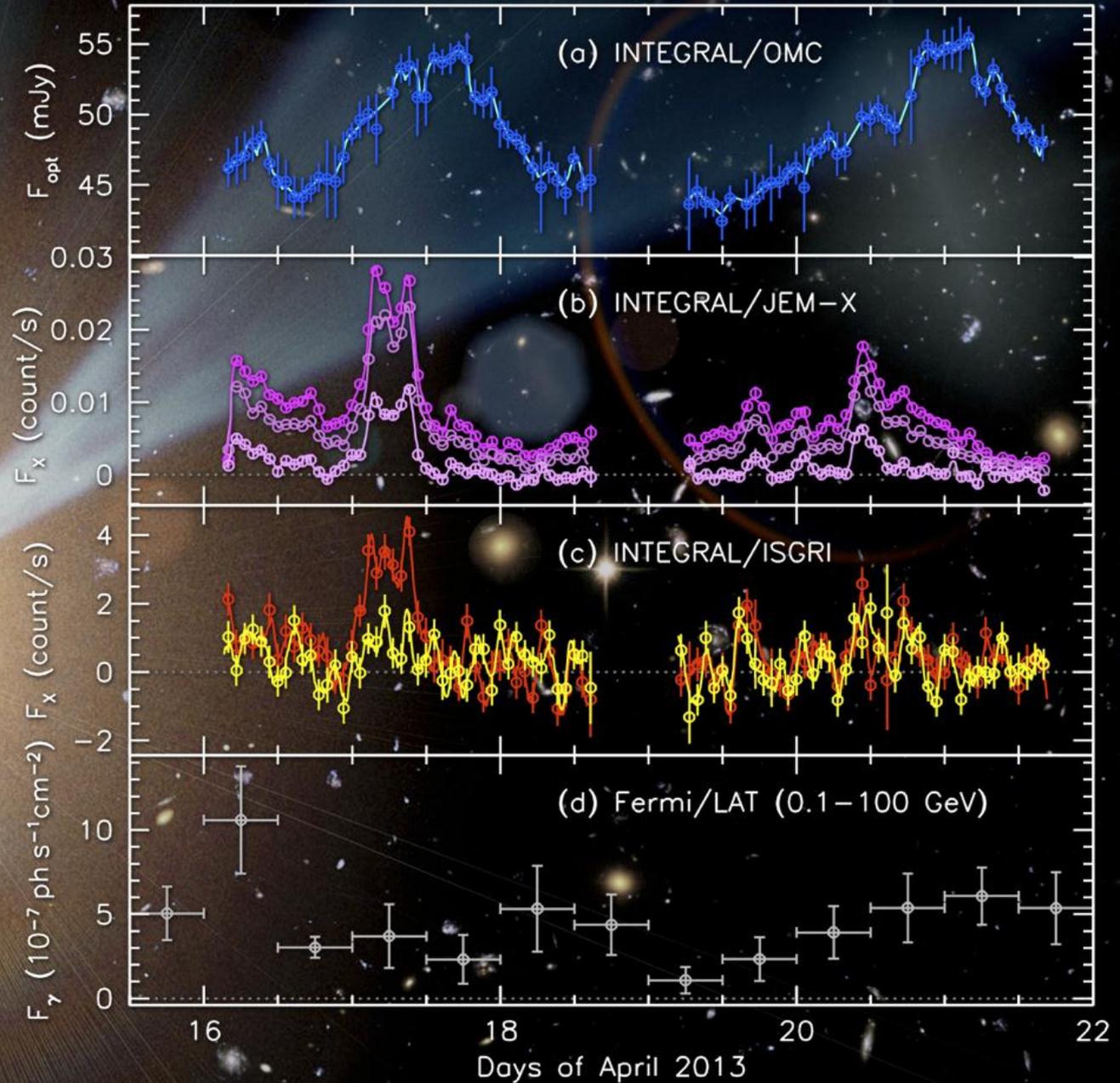
Lichti et al. (2008)

Mrk 421
2006 / 2008



Acciari et al. (2008)

Blazar Markarian 421 in Outburst



INTEGRAL Picture
of the Month
November 2013

X-Ray Polarimetry

Compton Polarization

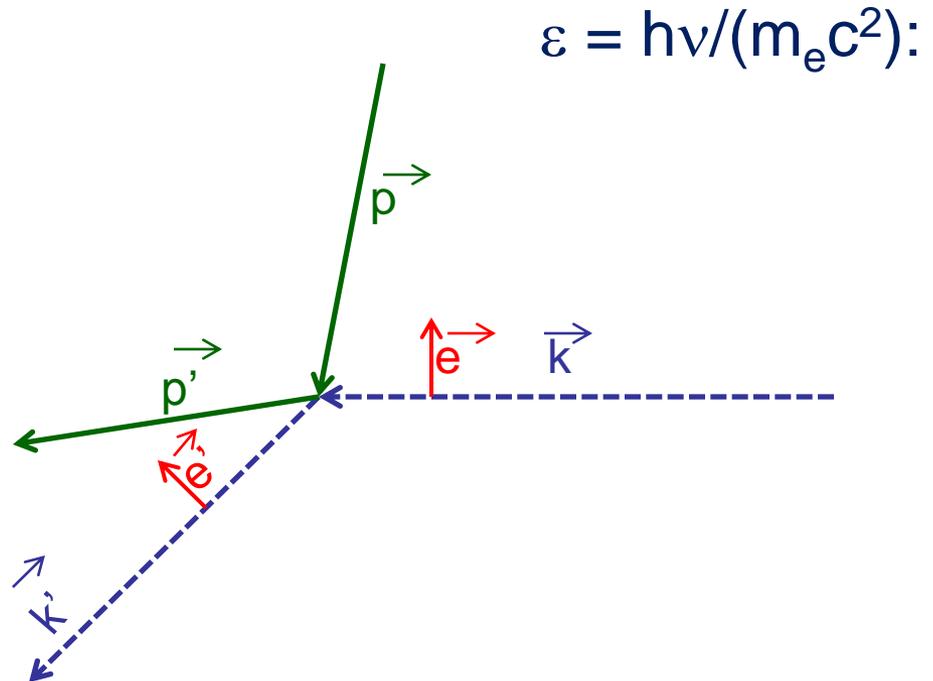
Compton cross section is polarization-dependent:

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{4} \left(\frac{\epsilon'}{\epsilon} \right)^2 \left(\frac{\epsilon}{\epsilon'} + \frac{\epsilon'}{\epsilon} - 2 + 4 [\vec{e} \cdot \vec{e}']^2 \right)$$

Thomson regime: $\epsilon \approx \epsilon'$
 $\Rightarrow d\sigma/d\Omega = 0$ if $\vec{e} \cdot \vec{e}' = 0$

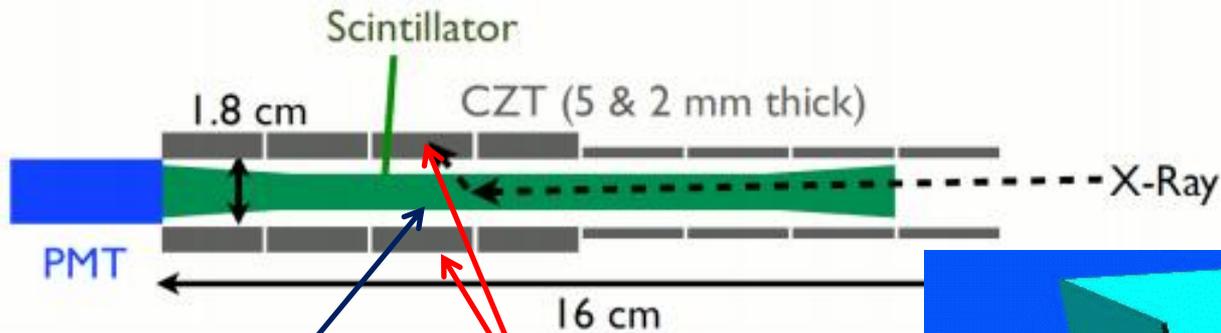
\Rightarrow Scattering preferentially in the plane perpendicular to \vec{e} !

Preferred polarization direction is preserved.



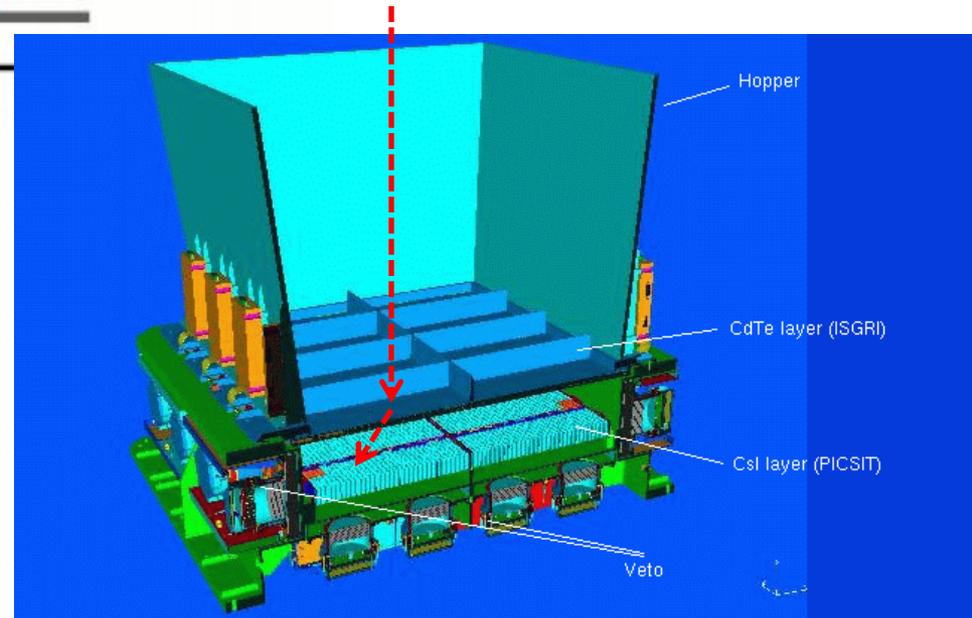
X-ray Polarimetry

General idea:



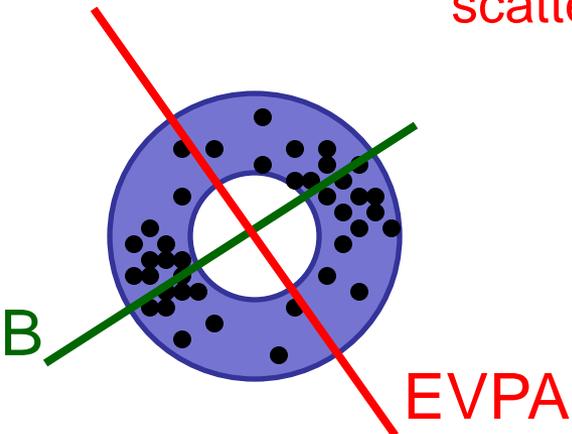
Single Compton Scattering

Look for bi-polar anisotropy of scattered photons



In IBIS:

Single scattering in ISGRI
→ anisotropic signal in PICsIT.

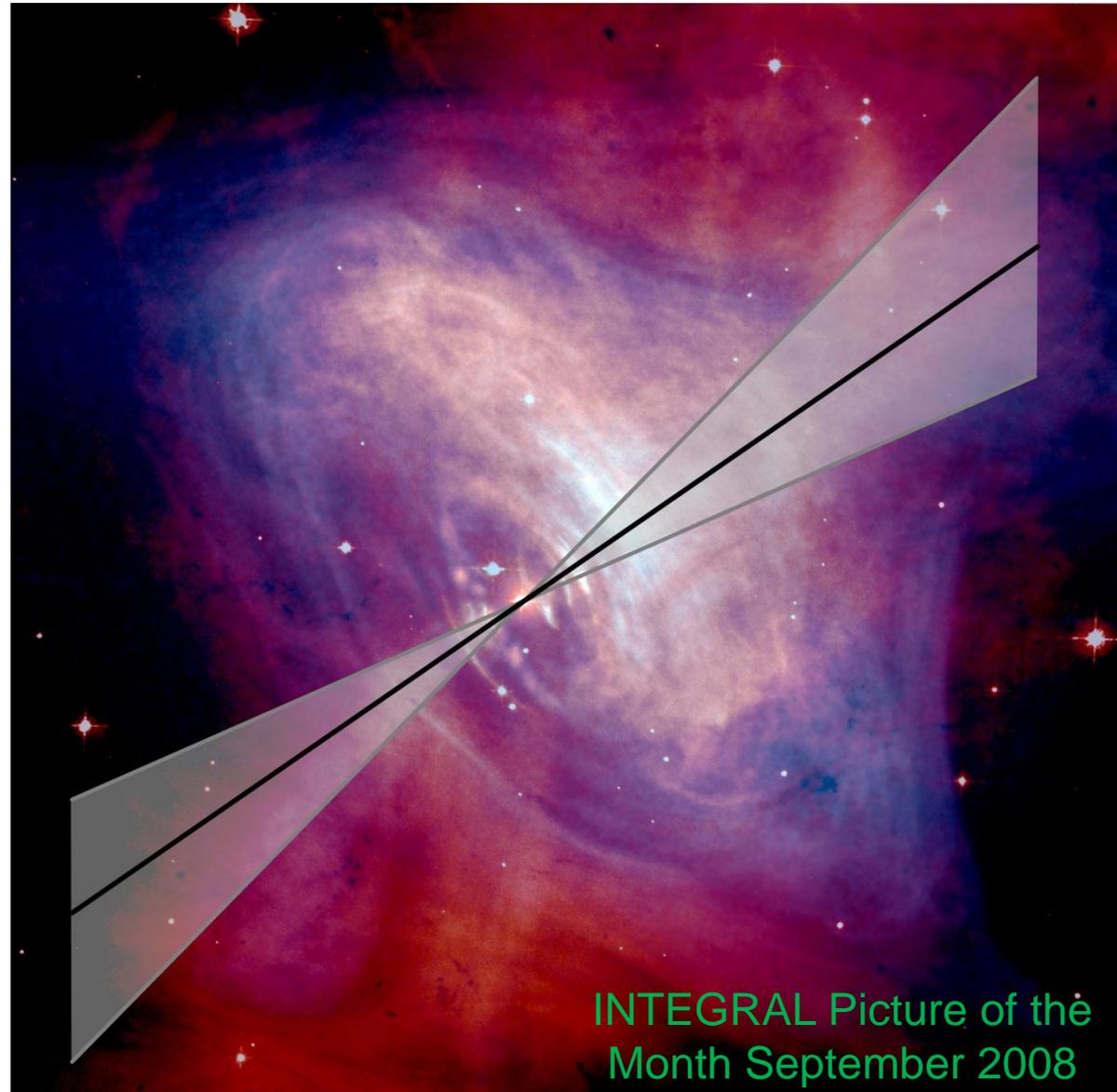


X-Ray Polarimetry: Pulsars

Crab Nebula / Pulsar:

High degree of polarization (46 ± 10 % at 0.1 – 1 MeV; 72 % at 200 – 800 keV); PA consistent with pulsar jet axis (Dean et al. 2008; Forot et al. 2008)

→ Highly ordered B-field structure and particle outflow.



X-Ray Polarimetry: GRBs

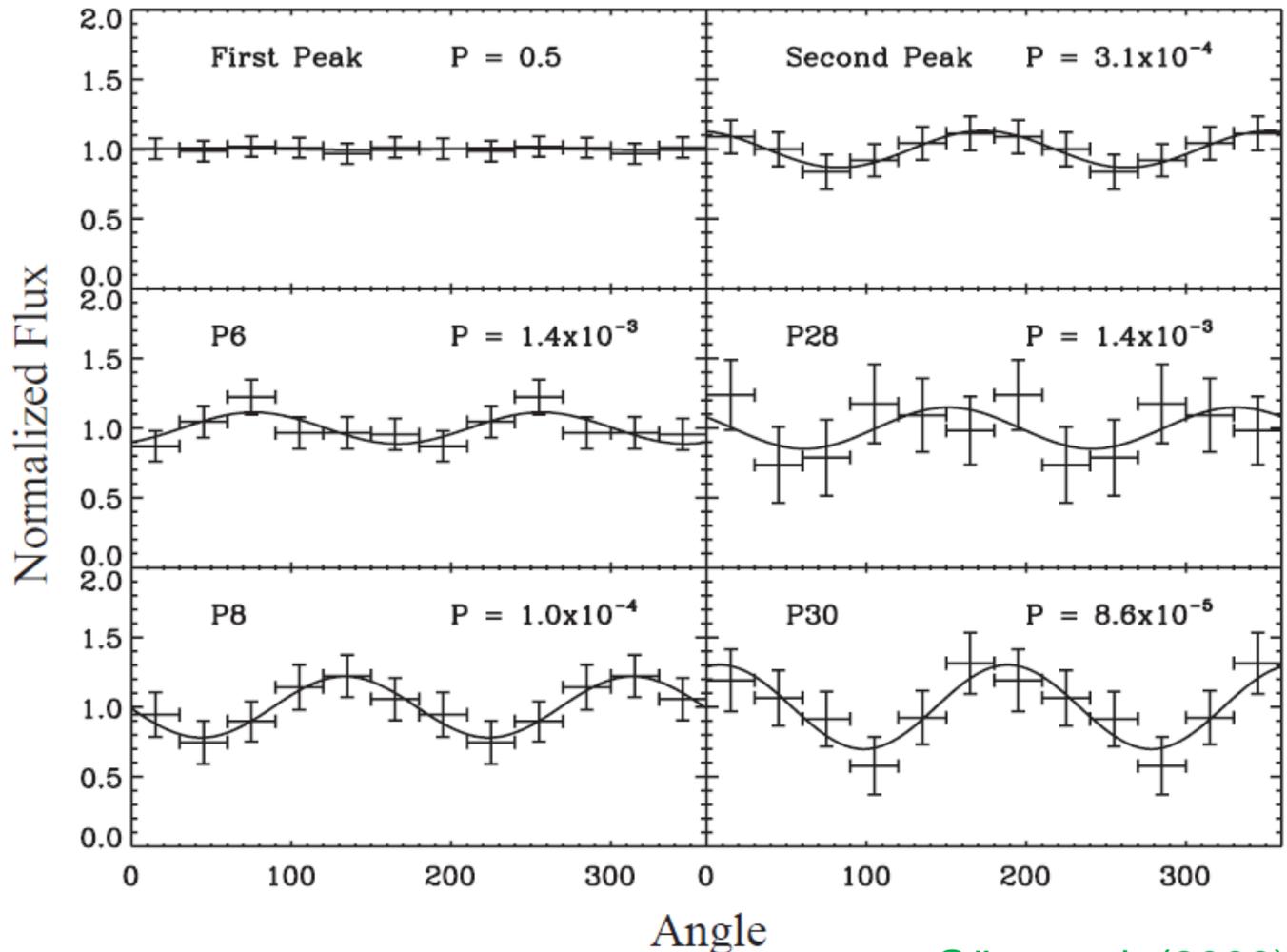
GRB 041219A

Claimed very high degree of polarization; controversial:

For
GRB 041219A:

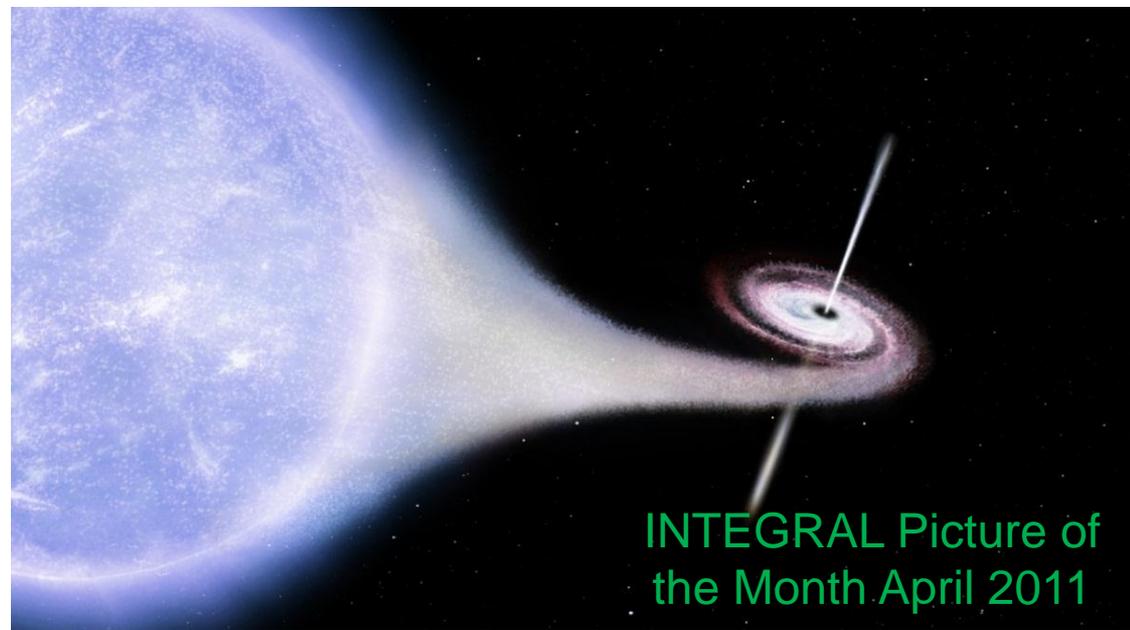
SPI: > 90 %

IBIS: 22 – 90 %

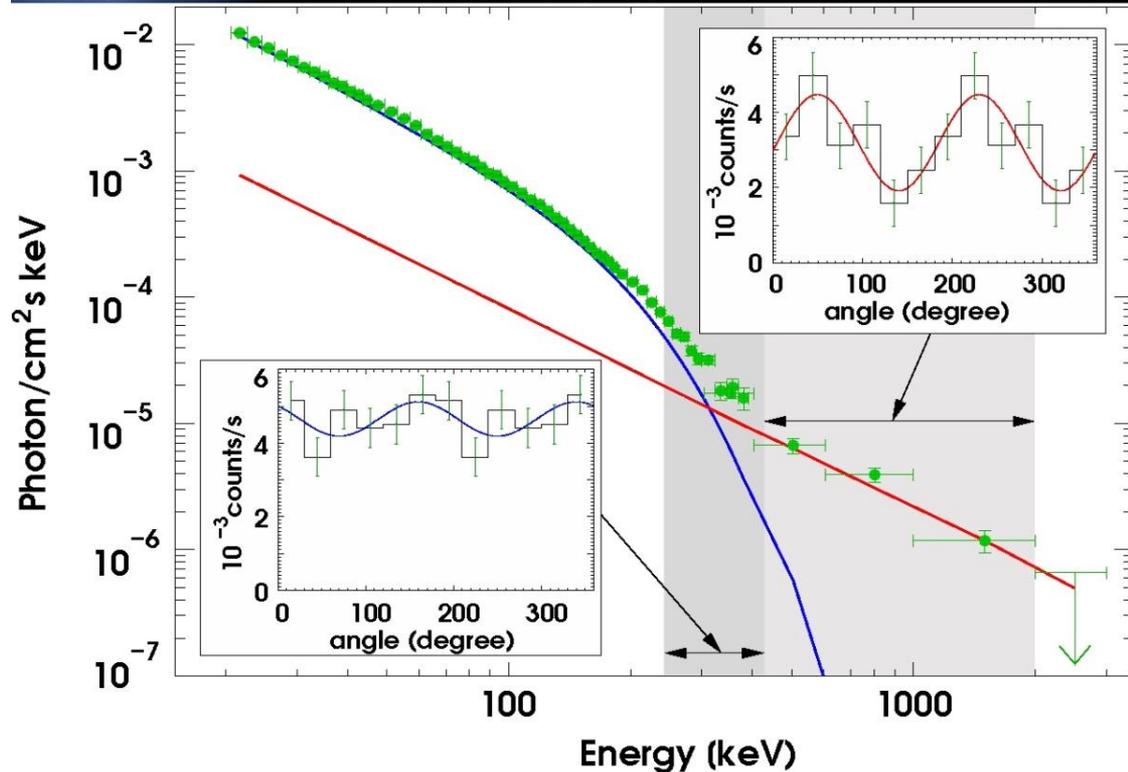


Götz et al. (2009)

X-Ray Polarimetry - XRBs



X-Ray Polarization
in Cyg X-1 primarily
associated with hard
(non-thermal) tail



Summary and Outlook

1. INTEGRAL's combined hard X-ray / soft γ -ray **imaging + spectroscopy** capabilities remain unparalleled for the near future.
2. Important for
 - γ -ray line studies (nucleosynthesis; positron annihilation)
 - Obscured HMXBs and AGNs (\rightarrow accretion geometry in HMXBs and AGNs; AGN unification; Hard X-ray background)
3. Continuum sensitivity not much better than predecessors; better sensitivity needed for LSP blazars ("MeV blazars"?)
4. X-ray / γ -ray polarimetry remains a frontier in high-energy studies; several X-ray polarimeter developments underway and proposed for next SMEX.

